Biophysics of magnetic orientation: strengthening the interface between theory experimental design by J. L. Kirschvink, M. Winklhofer, M. M.. Walker

Supplementary material

Geomagnetic intensity fluctuations over geological time The typical geomagnetic intensity over geological and evolutionary time scales has been lower than present – sometimes much lower. Animals have lived and migrated on this planet for at least the past 542 million years, and the presence of the colour effects on compass behaviour on a diverse group of animals suggests that this system evolved in a primitive form almost at the time of the Cambrian Explosion (see below). However, over geological time the Earth's magnetic field has experienced great fluctuations in its total intensity and direction, with some long intervals during which it was at only a few percent of its present strength (Selkin & Tauxe 2000). The field was particularly weak during the major radiation of the Birds in Cretaceous time, and has only been unusually strong on average during the past half million years (Granot et al. 2007; Tauxe 2006). As shown in Leonhardt et al., (2009) (Fig 4a therein and Fig 4a here) during the Laschamp geomagnetic excursion 41,000 years ago, huge portions of the planet had fields much lower than 10 μT, including most of the North Atlantic region, from the Pole to the Equator. As can be seen in Fig 4a here, at the climax of the excursion, the field in Europe was generally less than < 4 μT with values as low as 2 μT along the southwestern bird migration corridor to Morocco (Northwest Africa). This situation is similar to that of the last geomagnetic reversal, at the climax of which Europe experienced fields generally weaker than 4 μT (Fig. 4b). These periods of very low field strength last on the order of several hundred years, which is tens to hundreds of animal generations, depending on the organism.

A possible evolutionary scenario for the optical effect on a magnetite-based magnetic compass. Given the phylogeny of biogenic magnetite, the last common ancestor of all animals probably had a primitive, axially-symmetric magnetic compass receptor (Kirschvink & Hagadorn 2000). Due to the secular changes in the geomagnetic field, migratory animals need to calibrate their magnetic compass against the sun and star compasses on a regular basis (Cochran et al. 2004; Courtillot et al. 1997). The best time for them to do this would be at sunset and sunrise, when the position of the sun is usually easy to determine, even on cloudy days. Indeed, twilight calibration of the magnetic compass has been reported in several species (reviewed by Muheim et al. (2006)), although with at least one exception (Wiltschko et al. 2008). However, the best method for a primitive animal to detect sunrise and sunset would be for them to determine when blue light fades away (red light is present during the entire day, so the relative absence of blue light is a better indicator at the sensory level). Phylogenetic studies of the visual pigments in animals have shown that the most primitive forms were probably sensitive in the red, long-wavelength end of the spectrum (Davies et al. 2009; Yokoyama 2008). As colour vision arose via gene duplication events, the ancestor could only have had monochromatic vision, and thus would not have been able to determine from the visual spectrum the proper time for calibrating its magnetic compass. A cell expressing cryptochromes, however, would be activated by blue light, and could have been incorporated into a neurological/regulatory role for activating use of the axial magnetic compass system. All of this would most likely pre-date Middle Cambrian Time, as there is excellent evidence that animals in the Burgess Shale possessed colour vision (Parker 1998). The Rf-sensitivity would simply be a side effect of the use of the cryptochrome core. Before humans came along and invented radio transmitters there would have been no natural selection pressure against, or biological relevance for, this effect.

References:

Cochran, W. W., Mouritsen, H. & Wikelski, M. 2004 Migrating songbirds recalibrate their magnetic compass daily from twilight cues. *Science* **304**, 405-408.

Courtillot, V., Hulot, G., Alexandrescu, M., le Mouel, J. L. & Kirschvink, J. L. 1997 Sensitivity and evolution of sea-turtle magnetoreception: observations, modelling and constraints from geomagnetic secular variation. *Terra Nova* **9**, 203-207.

Davies, W. L., Carvalho, L. S., Tay, B. H., Brenner, S., Hunt, D. M. & Venkatesh, B. 2009 Into the blue: Gene duplication and loss underlie color vision adaptations in a deep-sea chimaera, the elephant shark Callorhinchus milii. *Genome Research* **19**, 415-426.

Granot, R., Tauxe, L., Gee, J. S. & Ron, H. 2007 A view into the Cretaceous geomagnetic field from analysis of gabbros and submarine glasses. *Earth Planet. Sci. Lett.* **256**, 1-11.

Kirschvink, J. L. & Hagadorn, J. W. 2000 A Grand Unified theory of Biomineralization. In *Biomineralization* (ed. E. Bäuerlein), pp. Ch. 10, pp. 139-150. Weinheim, Germany: Wiley-VCH Verlag GmbH.

Leonhardt, R. & Fabian, K. 2007 Paleomagnetic reconstruction of the global geomagnetic field evolution during the Matuyama/Brunhes transition: Iterative Bayesian inversion and independent verification. *Earth Planet. Sci. Lett.* **253**, 172-195.

Leonhardt, R., Fabian, K., Winklhofer, M., Ferk, A., Laj, C. & Kissel, C. 2009 Geomagnetic field evolution during the Laschamp excursion. *Earth Planet. Sci. Lett* **278**, 87-95.

Muheim, R., Moore, F. R. & Phillips, J. B. 2006 Calibration of magnetic and celestial compass cues in migratory birds - a review of cue-conflict experiments. *J. Exp. Biol.* **209**, 2-17.

Parker, A. R. 1998 Colour in Burgess Shale animals and the effect of light on evolution in the Cambrian. *Proc. R. Soc. London B* **265**, 967-972.

Selkin, P. A. & Tauxe, L. 2000 Long-term variations in palaeointensity. *Phil. Trans. R. Soc. Lond. A* **358**, 1065-1088.

Tauxe, L. 2006 Long-term trends in paleointensity: The contribution of DSDP/ODP submarine basaltic glass collections. *Phys. Earth Planet. Inter.* **156**, 223-241.

Wiltschko, R., Munro, U., Ford, H. & Wiltschko, W. 2008 Contradictory results on the role of polarized light in compass calibration in migratory songbirds. *J. Ornithol.* **149**, 607-614.

Yokoyama, S. 2008 Evolution of dim-light and color vision pigments. *Ann. Rev. Genom. Hum. Genet.* **9**, 259-282.